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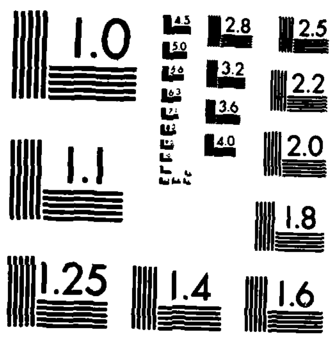

MICROCOPY RESOLUTION TEST CHART
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AN OVERVIEW OF ACOUSTIC DETECTION ANALYSIS

William J. Hurley

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AN OVERVIEW OF ACOUSTIC DETECTION ANALYSIS

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AN OVERVIEW OF ACOUSTIC DETECTION ANALYSIS

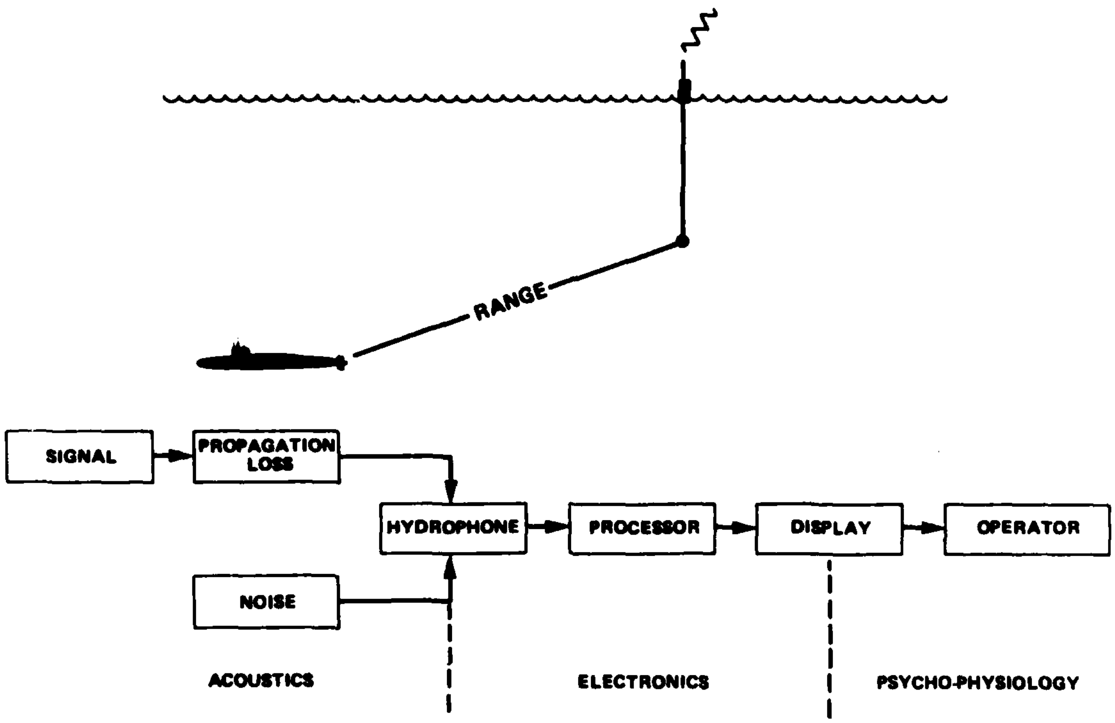
- NATURE OF THE PROBLEM
- BASIC APPROACH
- SOME COMPUTER TOOLS
- COMPARISONS WITH "REALITY"

Slide 1

SLIDE #1

I would like to review from the U.S. point of view the approach usually taken in analyzing the acoustic detection process, and some methods that are used to check--on those few occasions when we do--whether our descriptions bear any resemblance to what actually happens. For our group, I clearly do not have to review the importance of the detection phase to the whole ASW problem. It suffices to note that it drives the problem but is far from being all of it. Once detection is made, the succeeding phases of classification, localization and attack are no less critical. But for now, let's focus on this first crucial step of ASW. I would like to review the nature of the detection process, how we typically approach the analysis of it, some computer tools that are currently available and, finally, some aspects of how we compare our theoretical predictions with real-world data.

ACOUSTIC DETECTION PROBLEM



Slide 2

SLIDE #2

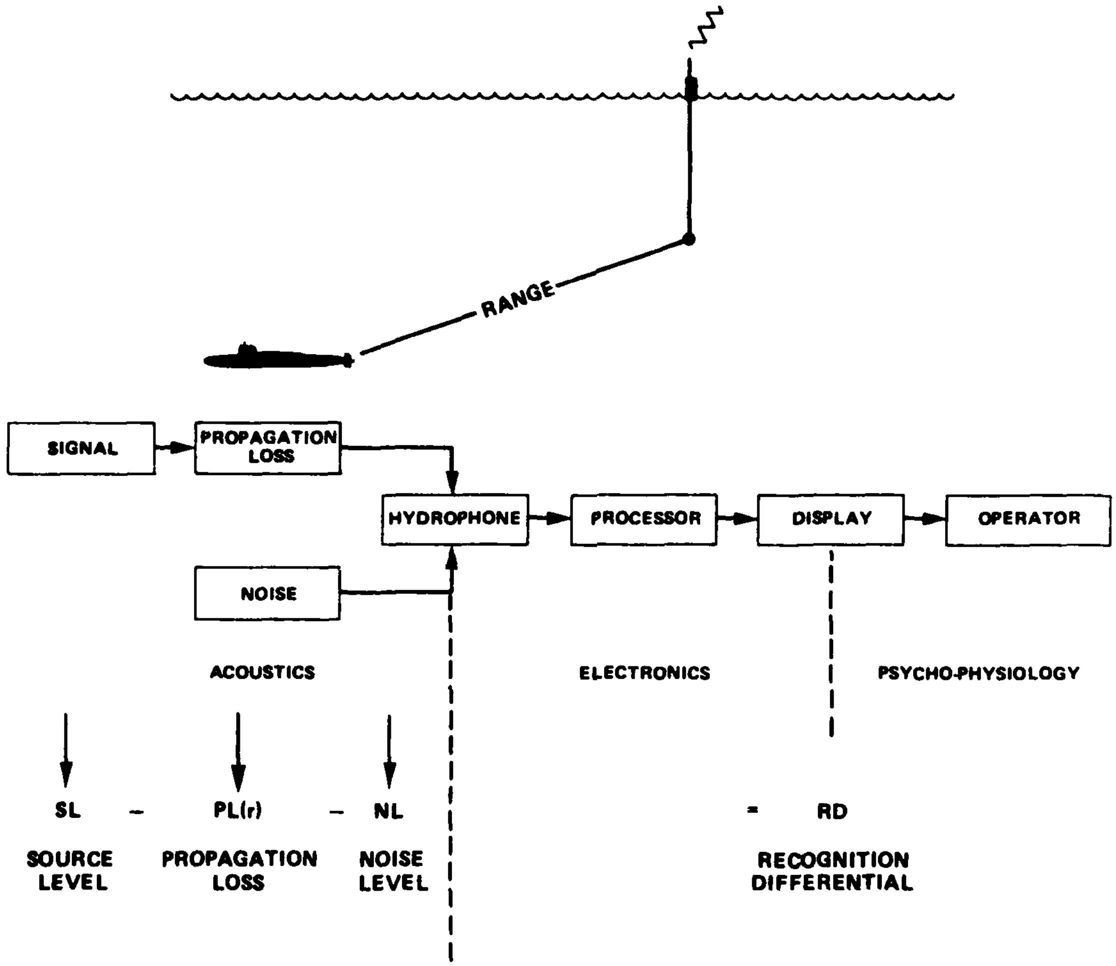
The nature of the acoustic detection problem is illustrated in this viewgraph. It has facets that are on the cutting edge of several disciplines: the physics of sound generation and transmission, oceanography, mechanical and electrical engineering, computer science and even human cognition. Fundamental research in each of these areas has reached a high level of sophistication and the results of that research are constantly finding new applications in succeeding generations of detection systems. Recently, advances in the electronics component have been the most dramatic. Indeed, future developments may see the elimination of the final stage depicted here as operators are replaced by automatic detection systems (which, the optimistic analysts believe, will be easier to analyze).

Now, each of these disciplines approaches the detection process in a different way. Each has different goals and correspondingly different requirements for detail and scope. And naval analysts' needs are different still. Our job is to attempt to "capture" this process in a way that, on the one hand, reflects all of the improvements that are being made but, on the other hand, is simple and tractable enough to be useful for the evaluation of tactical effectiveness. Our job is much the same as that of the thermodynamacist in physics who attempts to capture the macroscopic properties of a system in terms of a few quantities like pressure, volume and temperature without getting involved in the microscopic details of the forces and kinematics that so interest the molecular physicist. Of course, even within the charter of the naval analyst there is a wide spectrum of appropriate detail. The campaign analyst may well have to settle for a single "mean detection range" to characterize the effectiveness of a sonar throughout the campaign. On the other extreme, analysis of particular operations may have to consider such details as the directionality of the noise, radio channel monitoring capacity, and so on.

Let's steer a course between these two extremes and consider analyses that neither take gross averages of results, nor plunge too deeply into the details. Such analysis is typically appropriate for analyzing individual engagements (as opposed to campaigns) yet broad enough to be applicable to a relatively wide range of circumstances. This, in fact, constitutes the bulk of most analyses aimed at ASW systems done for planning (as opposed to operational) purposes.

As a generic example, consider the simple detection problem shown in the viewgraph: that of a single passive sonobuoy that does not listen preferentially in a given direction. The analyst describes this process by means of the sonar equation. I won't go into specific details but it goes something like as is indicated in the next viewgraph.

ACOUSTIC DETECTION PROBLEM



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SLIDE #3

The source level, SL, describes the intensity level of the "signal" generated by the target submarine. The analyst typically obtains its value from the intelligence community. The propagation loss, PL(r), where r is the range to the target, describes the loss in intensity due to the spreading and absorption in the water. The noise level, NL, measures the amount of noise at the hydrophone that competes with the arriving signal. PL(r) and NL are typically determined from publications that give geographic and seasonal values for these parameters.

The left-hand side of the equation is the residual intensity level of the signal arriving at the hydrophone. It refers entirely to the acoustic part of the problem. The right-hand side of the equation covers all the rest: the electronics, the computer processing, the display, and the operator's ability. This vast expanse of complexity is summed up in a single number, the Recognition Differential, RD, which is defined as the particular residual intensity level of the signal that would yield a 50 percent probability that the operator would call a detection. The recognition differential is a key parameter in detection analysis. There are men who earn their livelihoods calculating this number and they are said to be willing to wrestle you to the rug in defense of writing off a fraction of a decibel due to some new processing gadget. The analyst must typically rely on these experts for the RD value associated with a given sonar. A few such experts will clearly explain exactly how they arrived at the stated value but they are rare and will hardly ever put anything in writing.

Of course, the overall detection process is a lot more complicated than I have indicated--I didn't talk about beamforming, frequencies, integration times, pulse lengths, reverberation, and so on. However, these features would not change the fundamental notions that we have been considering.

But what kind of equation is this? We looked up all the terms. Where is the unknown?

SONAR EQUATION

$$\underbrace{SL - NL - RD}_{\text{FOM}} - PL(r) = SE(r)$$

SE(r) = SIGNAL EXCESS

FOM = FIGURE OF MERIT

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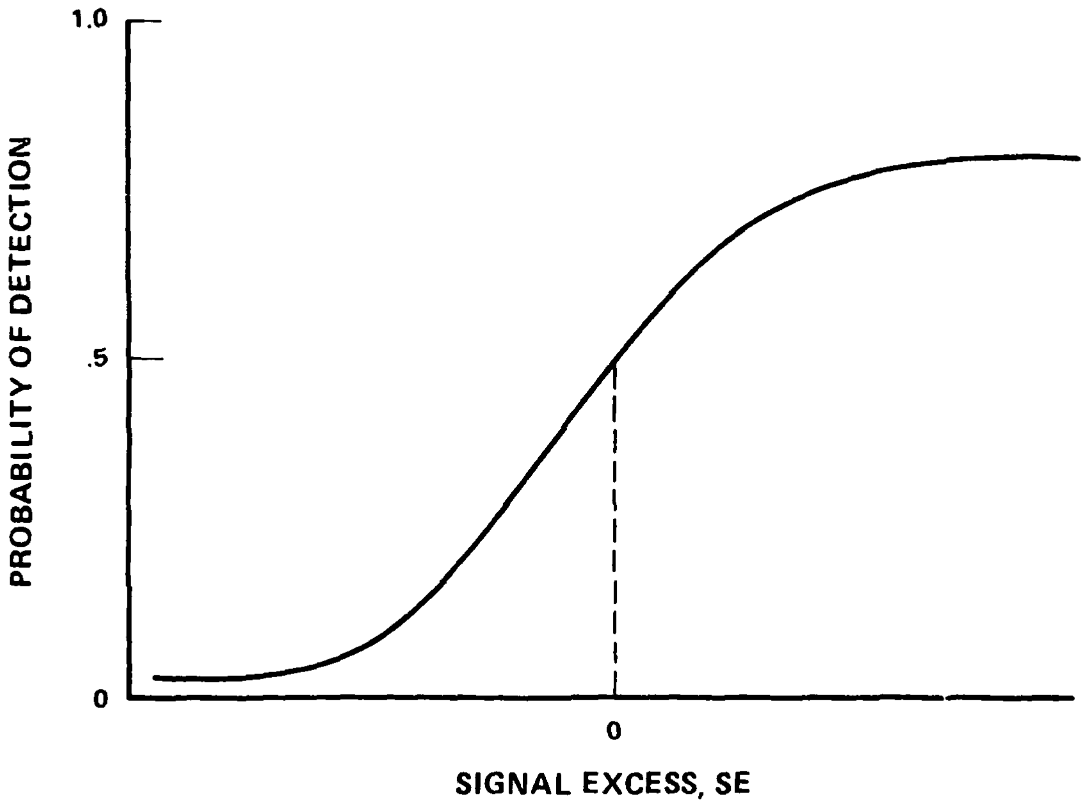
SLIDE #4

That is shown in this viewgraph. We bring RD over to the left-hand side and call the difference the signal excess, SE(r). [Note also that we can lump together all the terms that do not depend upon range and call it the "Figure of Merit" of the sonar.] In fact, from the analyst's viewpoint, the sole use of the sonar equation is to provide the values of SE(r). When SE(r) is zero, the sonar equation is satisfied and, by definition of the recognition differential, the probability of detection is 50 percent.

SIGNAL EXCESS

$$SL - NL - RD - PL(r) = SE(r)$$



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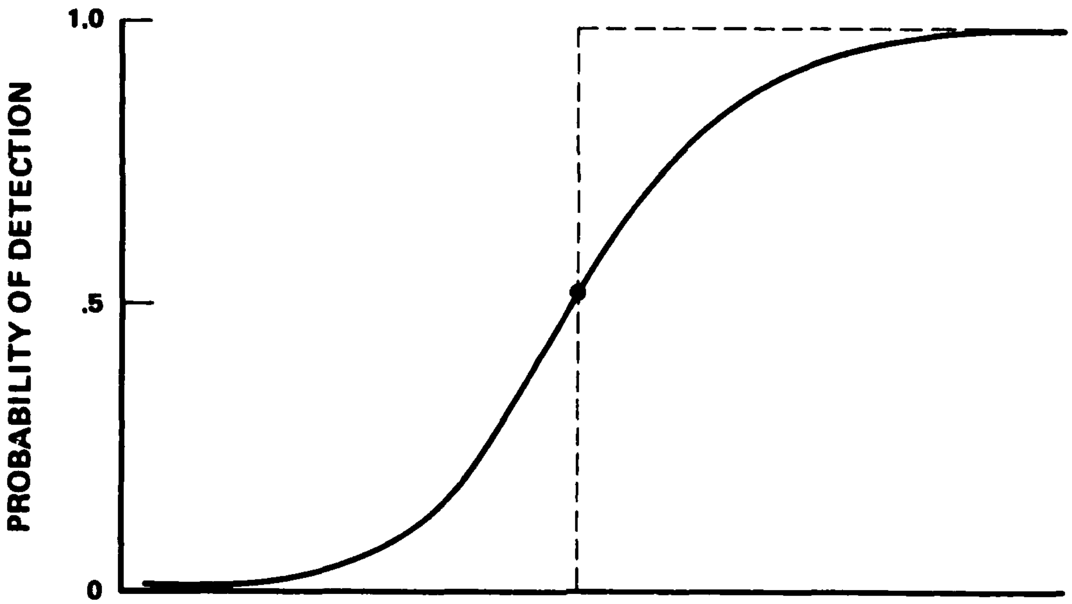
SLIDE #5

When SE is larger than zero, the probability of detection increases as is indicated on this viewgraph. As SE becomes negative, then the probability of detection decreases. So for each detection process we have a relationship between the signal excess and the resultant probability of detection.

THRESHOLD ASSUMPTION



$$p_d = \begin{cases} 1 & , SE \geqslant 0 \\ 0 & , SE < 0 \end{cases}$$

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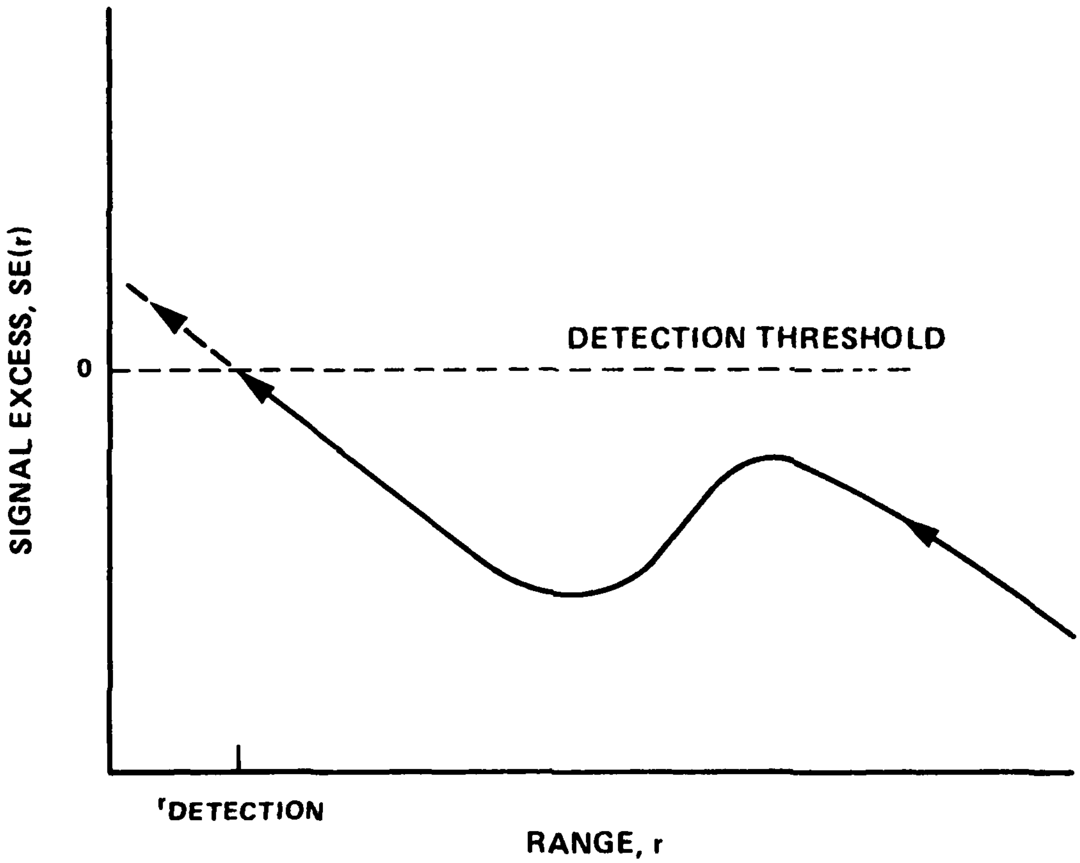
SLIDE #6

At this point, it is common to make an approximation that simplifies the analysis and is justifiable because the curve of P_d vs SE is usually very steep. We replace this curve with a step function as is indicated in this viewgraph. We thereby assume that a detection will always take place if the signal excess is greater than or equal to zero and will never take place if the signal excess is negative.

DETECTION THRESHOLD



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SLIDE #7

Thus, if we follow the target along its track, it is detected at the first point at which the signal excess is greater than or equal to zero.

DIFFICULTY WITH SIMPLE THRESHOLD MODEL

- **ALL DETECTION RANGES ARE THE SAME (FIRST r WHERE SE(r) $\geqslant$ 0)**

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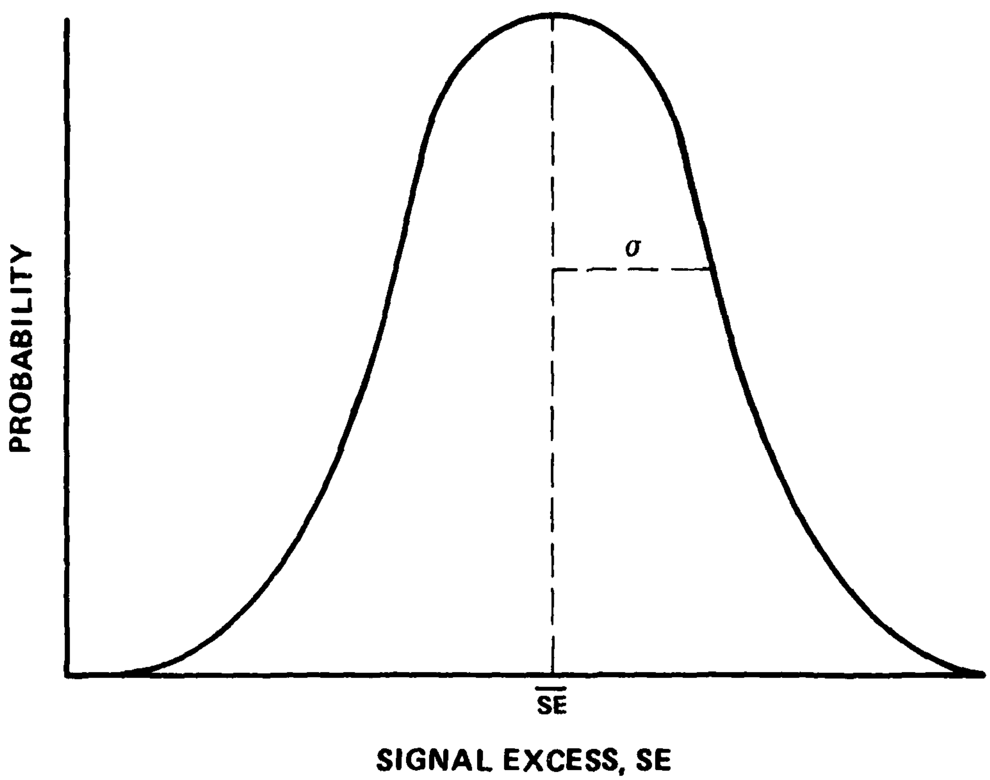
SLIDE #8

However, while this analysis is agreeably simple, for most cases it is blatantly unrealistic. Afterall, if we were to consider a number of engagements under similar circumstances, we would predict that detection would occur at exactly the same range in each case, a result that differs markedly from what is actually observed. Therefore, like good scientists, when the theory fails to agree with experiment--and we cannot destroy the reputation of the experimenter--we go back and reconsider the assumptions of the theory. When we do this, we see--as we have already noted--that we have assumed single values for quantities that really are highly variable: source levels of submarines vary with such particulars as speed and aspect; propagation loss and noise levels vary with location, season, time-of-day, and weather, and we have already noted that there are many (often hidden) assumptions that go into determining the value of the recognition differential. Finally, we have just discussed that, even if all of the contributions to the signal excess were precisely known, then there would still be some uncertainity whether a detection would in fact be made. We therefore acknowledge all of this uncertainty and declare that the signal excess is not exactly predictable.

SIGNAL EXCESS AS RANDOM VARIABLE



SE	=	$\overline{SE}$	+	X	
↓		↓		↓	
OBSERVED		SONAR EQUATION		GAUSSIAN MEAN = 0 σ	(N(0, σ))

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Rather, the signal excess is a random variable and the value given by the sonar equation is the mean value of this random variable. Furthermore, it is most often assumed that this random variable is Gaussian-distributed about the mean value. This is typically expressed as indicated by setting $SE = \overline{SE} + X$ where $\overline{SE}$ is the mean value as given by the sonar equation and X is a mean-zero, Gaussian-distributed random variable with standard deviation sigma. The standard deviation, is a critical parameter that describes the variability of the signal excess and therefore also the variability of the detection ranges. Its value, however, is often taken on the basis of "traditional rules of thumb" or just plain folklore. The resultant slipperiness of this critical parameter is perhaps second only to that of the recognition differential.

By interpreting the output of the sonar equation as the mean value of a random variable, we are able to convert this output into a more realistic probability of detection.

INSTANTANEOUS PROBABILITY OF DETECTION

NON-VARIABLE SE:

$$P_d = \begin{cases} 1, & SE > 0 \\ 0, & SE < 0 \end{cases}$$

VARIABLE SE:

$$\begin{aligned} P_d &= Pr(SE > 0) \\ &= Pr(\overline{SE} + X > 0) \\ &= Pr(X < \overline{SE}) \\ &= \frac{1}{(2\pi)^{1/2}\sigma} \int_{-\infty}^{\overline{SE}} \exp\left\{-y^2/2\sigma^2\right\} dy \end{aligned}$$

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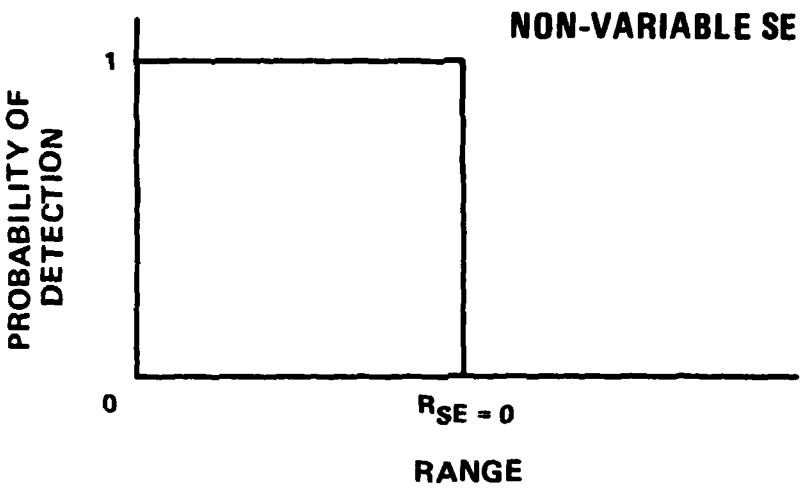
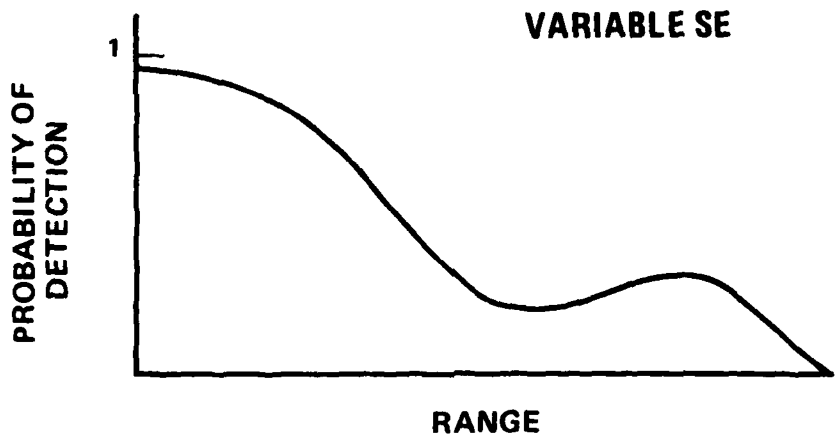
Thus, the rigid formulation on the top of the viewgraph is replaced by a probabilistic formulation which yields the probability, at any instant in time, that the signal excess will be greater than, or equal to zero. This probability is referred to as the instantaneous probability of detection and it is calculated from the mean signal excess, $\overline{SE}$, and the standard deviation, sigma, as is indicated.

DETECTION RANGE VARIABILITY





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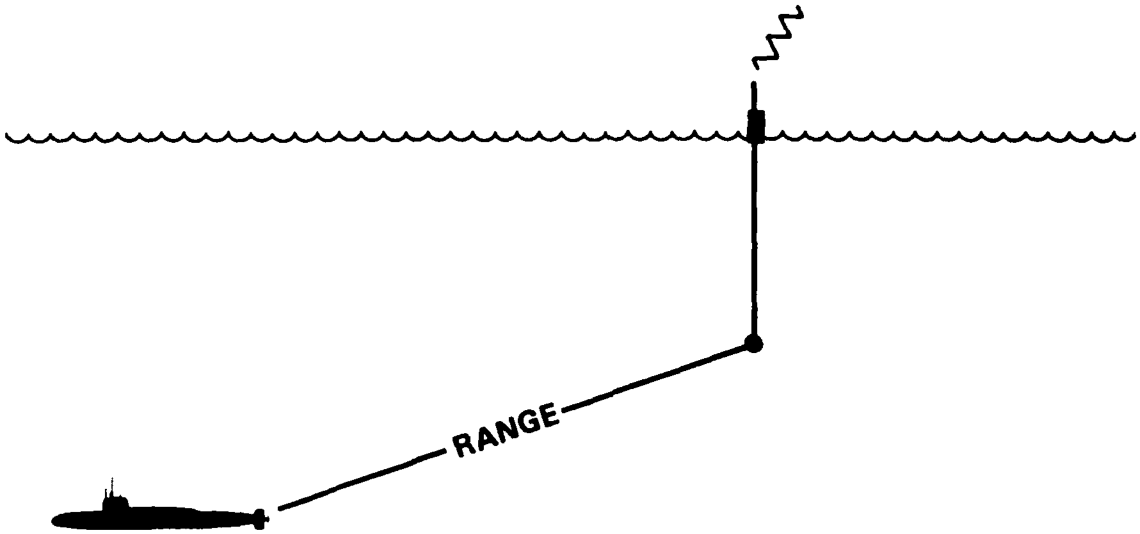
SLIDE #11

We thereby gain a more realistic variability in the probabilities of detection, as is indicated in this viewgraph, and a resultant variability in the predicted detection ranges.

So far, we have gained a more realistic spread of the predicted detection ranges but there remains another critical dimension of the detection process: time.

TIME-TO-DETECT



P_d = .3 PER CHANCE

HOW MANY CHANCES PER HOUR?

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Suppose, to keep it as simple as possible, we have a stationary target a distance r from a stationary hydrophone. Suppose that we calculate the signal excess, choose an appropriate sigma and find the resultant instantaneous probability of detection to be 0.3. Now, suppose that the target stays at range r for hours--continuing to radiate its signal. Does the cumulative probability of detecting the target increase or stay at 0.3? If we failed to detect the target, how long do we have to wait for another chance? The answer depends on the underlying variability of the process. For example, if the variability were due primarily to surface waves, then we should get a new chance every few seconds or so. On the other hand, if the variability is due primarily to the differences in the material condition of the sonobuoys, then a given sonobuoy should get only one independent chance to detect.

Thus, how often we get to draw a new value of X from the Gaussian distribution and therefore get a new chance to cross the SE = 0 threshold depends upon the nature of the underlying detection process. If we can draw frequently, our chance of pulling an X which puts us over the threshold is greatly enhanced. But if new draws are not allowed, we have the initial chance of detecting of 0.3 and if we don't detect then, we never will.

Therefore, the choice of how often a new value of the random variable is taken is critical to the results of any analysis of detection performance.

For simplicity, we have discussed this in terms of a stationary target but the more realistic case is that of a target following a track with respect to the detector. The question of how often the searcher is allowed a "new" draw from the X distribution is therefore cast into the notion of the correlation of detection opportunities along the track. There are many models of this aspect of the detection process.

SOME MODELS OF TIME CORRELATIONS

	PARAMETERS
• INDEPENDENCE (OVER TIME T)	σ, T
– ANALYTICAL SOLUTION	
• COMPLETE DEPENDENCE	σ
– X FIXED OVER EACH ENCOUNTER	
– ANALYTICAL SOLUTION	
• LONG-PLUS-SHORT	σ_l, σ_s, T
– $X = X_l + X_s$ (ALL $N(0, \sigma)$)	
– SIMULATION	
• $\lambda - \sigma$ JUMP	σ, λ
– X $N(0,\sigma)$	
– $p(T) = \lambda e^{-\lambda T}$	
– SIMULATION	
– SOME ANALYTICAL	

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And here is a list of some of the more popular ones. Note that we have nowhere near the consensus that we had with the Gaussian distribution for the signal excess.

The independence model assumes that an independent detection opportunity occurs after each time interval T. The resultant cumulative probability of detection is easily calculated. The parameters that must be chosen are the standard deviation of the Gaussian distribution, sigma, and the time interval T. As with all of these models, the results are very sensitive to the choice of these parameters. If T is very small, then the cumulative probability of detection approaches one.

On the other hand, if T is chosen to be much larger than a typical encounter time, then we get the complete dependence model where the random component, X, is fixed over each encounter. This case is also easily solved since the cumulative probability of detection is just the maximum of the instantaneous probabilities along the track. Only the parameter sigma need be chosen.

The rest of the models are intermediate between the independence and complete dependence models. The long-plus-short model decomposes the random component into a long-term component drawn for each encounter from a Gaussian distribution with standard deviation sigma-l, and a short term component which is drawn from another Gaussian distribution with standard deviation sigma-s at time intervals T along the targets's track. There are no analytical solutions to this model but it is easily simulated on a computer.

The lambda-sigma jump model, which was introduced by J. D. Kettelle, is one of the most popular. Like the others, it draws X from a Gaussian distribution, but the time interval between draws is not held fixed. Rather, it too is considered to be a random variable that is exponentially distributed as shown. The cumulative detection probabilities are therefore driven by the choices of sigma and lambda. This model is easily simulated and, even better, there are analytical solutions for many important cases.

SOME MODELS OF TIME CORRELATIONS

PARAMETERS

- **GAUSS – MARKOV** σ, λ

  – $p(X_k \mid X_{k-1}) = \dfrac{1}{\sigma[2\pi(1-\rho^2)]^{1/2}} \exp\left\{-\dfrac{(X_k - \rho X_{k-1})^2}{2\sigma^2(1-\rho^2)}\right\}$

  $$\rho = e^{-\lambda(t_k - t_{k-1})}$$

  – **SIMULATION**

- **HALF-AND-HALF** σ, T, α

  – $P_d(t) = \alpha\, P_d^{IND}(t) + (1-\alpha)\, P_d^{DEP}(t)$

  – e.g., $\alpha = \dfrac{1}{2}$

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The Gauss-Markov model is also governed by two parameters, and it offers the additional feature of having the value of X at the instant K depend upon the value of X at the previous instant, K-1. This feature eliminates the sharp discontinuities that are characteristic of the lambda-sigma jump model. There are no general analytical solutions to the Gauss-Markov model, but it is easily simulated.

Finally, we have the half-and-half approximation. This approximation leads to results that are intermediate between the independence model and the complete dependence model. We simply calculate the cumulative probability of detection for the exteme cases and combine the two with a weighting factor, alpha. The name derives from the most popular choice of alpha: one-half.

I will not attempt to go into any more detail on these models of time correlations. I wish only to point out that all too often it appears that the model's parameters such as sigma and lambda are chosen, not on the basis of the nature of the particular situation, but rather according to some traditional, non-controversial or previously "blessed" values--the rational basis for which is lost in antiquity. There is a great deal of need for support for some hard-nosed, empirically based work in this area.

These models address correlations at different points in time for a single detector. What about correlations between several spatially separated detectors--like a field of sonobuoys?

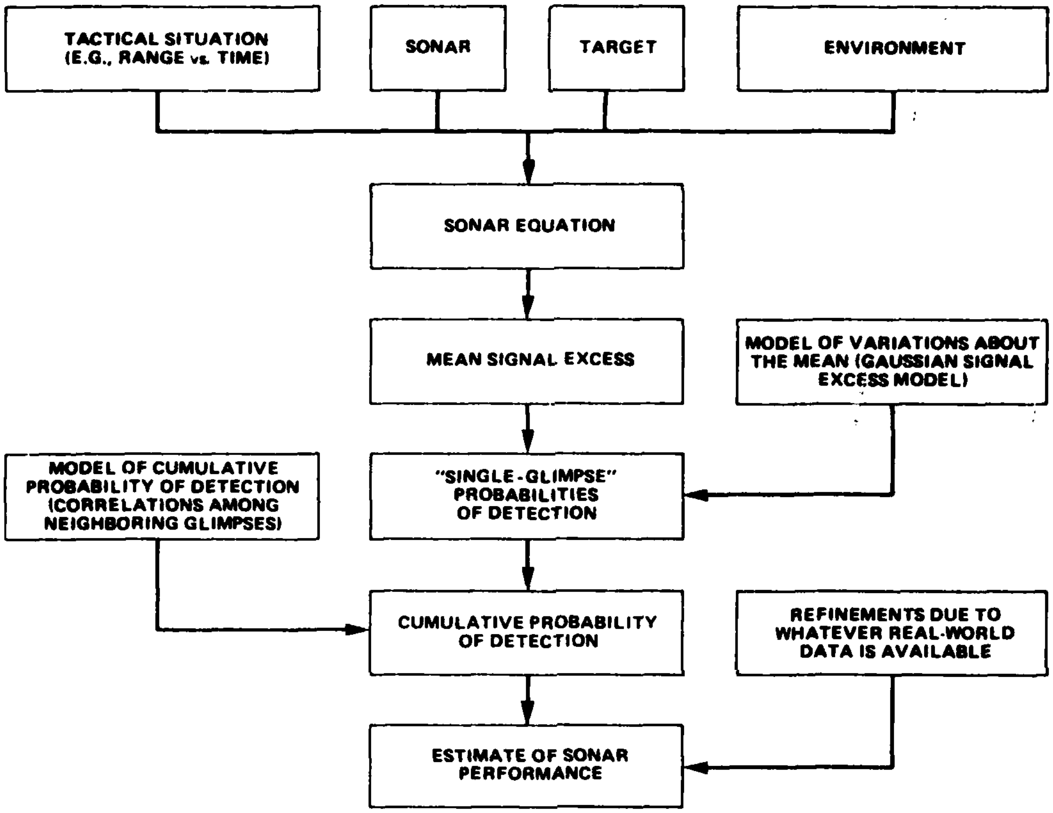
SPATIAL CORRELATIONS

- THERE IS SOME MODELING SIMILAR TO TIME CORRELATIONS
- HALF-AND-HALF APPROXIMATION WIDELY USED
- NEED FOR ADDITIONAL WORK

SLIDE #15

Should each detector get an independent chance to detect or are neighboring detectors highly correlated? There are models similar to the above for dealing with this aspect of the problem. For example, the analog of the long-plus-short model assigns a random component drawn for the whole sonobuoy field and another which is drawn for each sonobuoy. However, far less attention has been paid to spatial correlations than has been paid to time correlations. The result is that even some very sophisticated models may still invoke a "half-and-half" approximation for spatial correlations.

SCHEMATIC OF THE ANALYSIS OF SONAR PERFORMANCE



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This viewgraph sums up schematically the analysis of sonar performance.

The analyst begins by quantifying the tactical situation, the sonar, the target, and the environment in terms of a few parameters that go into the sonar equation. The output of the sonar equation is the mean signal excess which, when combined with a model of the variations about the mean, produce the "instantaneous" or "single-glimpse" probabilities of detection. These probabilities are then combined with a model of correlations among neighboring detection opportunities to yield the cumulative probability of detection as the encounter unfolds. Finally, whenever possible, the theoretical results should be refined by whatever real-world data may be relevant in order to arrive at a final estimate of sonar performance.

Now, it's hard enough to carry out a detection analysis for the simple example that we have been considering. In order to keep account of different tracks, tactics, multiple sensors, etc., we must resort to computer-assisted models. These are all built around the basic modeling tools that we have been discussing, but they help keep track of the complexities that are characteristic of a more realistic engagement.

SOME COMPUTER MODELS

- "AP" SERIES
  - APAIR
  - APSUB
  - APSURF
- SIM II
- SCREEN

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SLIDE #17

Here is a list of some of the more popular models.

The "AP" series of models was introduced in the late sixties and early seventies. "AP" stands for "ASW Program." These models are large-scale Monte Carlo simulations of engagements from detection through attack and reattack. Each has over a hundred subroutines and over a thousand variables. They are written in FORTRAN IV or V for the IBM 360 series and similar machines. APAIR simulates a single aircraft against a single submarine. APSUB, which for the most part is now outdated, considers an engagement between two submarines. APSURF simulates a task force against a single target and may describe as many as 25 ships and 25 helicopters.

SIM II was introduced in the early seventies and has become the most popular model for simulating submarine vs submarine engagements. This model is extremely versatile due to its ability to accept English-language instructions for tactics. The model can also be used for surface and air platforms.

SCREEN was introduced by Wagner Associates in the late 70's. It's not a simulation but rather it calculates results analytically. It describes the acoustic detection and localization capabilities of ASW forces about high value shipping. One form of its output is a chart of the instantaneous detection probabilities around the force.

COMPARISONS WITH REAL-WORLD DATA

- NECESSARY FOR CREDIBILITY
- NEED FOR MORE ATTENTION
- STATISTICAL TECHNIQUES
  - DISTRIBUTION OF DETECTION RANGES
  - ESTIMATE OF DETECTION RANGE DISTRIBUTION VIA ANALYSIS OF OBSERVED DETECTION RANGES AND CPAs

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SLIDE #18

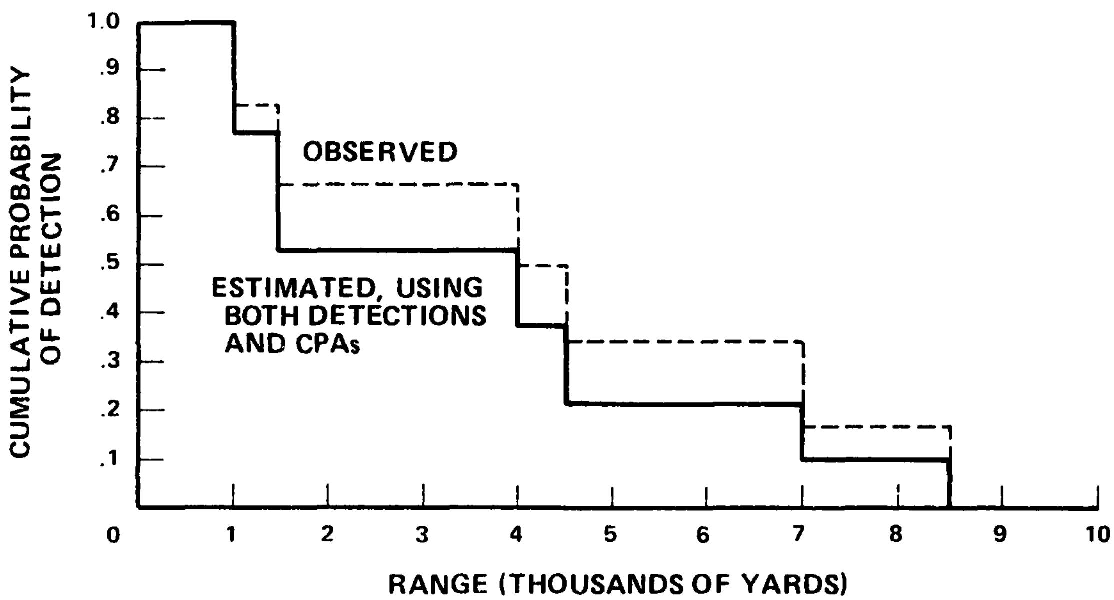
Finally, I would like to say a few words about comparing the results of detection analysis with real-world data. Afterall, this is our only source of credibility, yet far too little work is being done in this area.

One area which affects our ability to incorporate real- orld data is the statistical treatment of such data. For example, the use of observed detection ranges to test our predictions is particularly important.

Of course, when you only know the observed detection ranges you have no idea how many missed opportunities there were and therefore you cannot determine the overall probability of detection. However, when an exercise is reconstructed (which is an art in itself) we often do have both detection and opportunity data. How can we use such data to determine sonar performance? One way which uses a minimum of data, is to take all of the observed detection ranges, and closest points of approach for the undetected targets, and estimate the probability distribution of the sonar's detection range using a statistical technique due to Kaplan and Meier for use with incomplete data. This estimate has some desirable statistical qualities (for example, it is a maximum likelihood estimate) and leads to the kind of results shown in the next viewgraph.

EXAMPLE:
OBSERVED RANGES AT DETECTION OR CPA

EVENT	1	2	3	4	5	6	7	8	9	10
DETECTION/CPA	D	D	CPA	D	D	CPA	CPA	D	CPA	D
RANGE (THOUSANDS OF YARDS)	1.0	1.5	2.5	4.0	4.5	5.5	6.0	7.0	7.5	8.5



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Here we have some fictitious data for ten events. The detection events are denoted by D and the undetected events are denoted by CPA for closest point of approach. The events are ordered according to the range of the detection or CPA. Now, if we simply restrict our attention to the observed detection ranges and plot their distribution we get the upper dashed curve of the viewgraph. If we now include the missed opportunity data--the CPA events--and use the Kaplan-Meier estimate for the sonar detection range then we get the lower curve. We see that the estimate based on the distribution of detection ranges is refined downward--as is to be expected--when the missed opportunity data is included.

Now this is a convenient statistical technique but let's take a critical look at its underpinnings especially in light of our previous discussion on correlations along the target's track.

THE ENCOUNTER DEFINITE RANGE LAW (EDRL)

- DEFINITE (COOKIE-CUTTER) DETECTION RANGE FOR EACH ENCOUNTER

- DETECTION RANGE MAY VARY FROM ENCOUNTER TO ENCOUNTER

  $F(r) = Pr\ (\text{DET'N RANGE} \geq r)$

- CONSEQUENCES OF EDRL:
  - DETECTION OPPORTUNITIES COMPLETELY CORRELATED
  - NO POST-CPA DETECTIONS
  - EQUATES DIFFERENT MEASURES OF DETECTION PERFORMANCE, FOR EXAMPLE:

$P_d^{CCT}(r)$ = Pr (DETECT CONTINUOUSLY CLOSING TARGET AT OR BEFORE r)

AND

$L(r)$ = Pr (DETECT TARGET WHICH FOLLOWS A STRAIGHT TRACK WITH CPA = r)
= LATERAL RANGE CURVE

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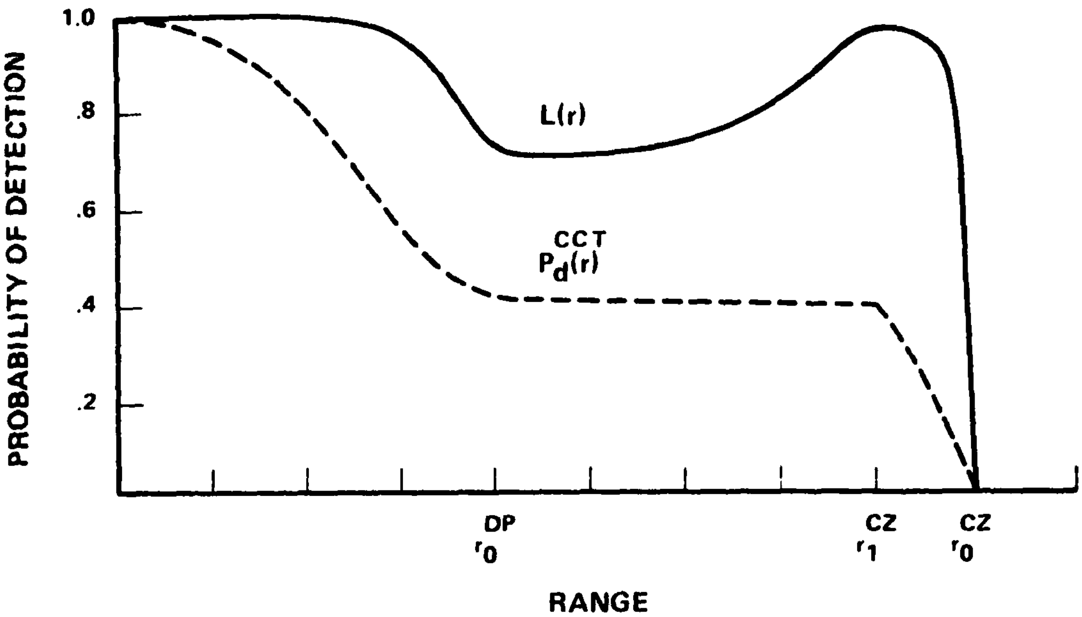
SLIDE #20

This estimate assumes that a so-called "Encounter Definite Range Law" is valid. This means that for each separate encounter there is a definite detection range associated with the detector. That is, the detector is described as a cookie-cutter with a range that is held fixed over each encounter but which may vary from encounter to encounter according to some probability distribution. It is this distribution, denoted by $F(r)$, that we are estimating from the data. Now the Encounter Definite Range Law may provide a convenient statistical technique but it also makes some very strong statements about the detection process itself. For example, it is generally equivalent to assuming that detection opportunities along the target's track are completely correlated. It therefore forbids any post-CPA detections (that is, detections made after the target has passed its closest point of approach) and it has strong implications for other commonly used measures of detection performance. For example, it implies that the cumulative probability of detection against a continuously closing target, i.e. the probability of detecting a closing target at or before it reaches range r denoted here by $P_d^{CCT}(r)$ is <u>identical</u> to the lateral range curve-denoted by $L(r)$. Recall that the lateral range curve is a graph of the cumulative probability of detection over an <u>entire</u> straight-line track whose closest point of approach is a distance r from the detector.

EXAMPLE: ACTIVE SONAR



- $P_d^{CCT}(r) \neq L(r)$
- WHEN IS THE "ENCOUNTER-DEFINITE-RANGE-LAW" VALID?

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That those two quantities may be vastly different in practice is illustrated in the next viewgraph which results from a somewhat more realistic treatment of an active sonar with a convergence zone detection capability. Note the great difference between the two curves that the encounter definite range law would imply are equivalent.

So we are left with the questions: When is the "encounter definite range law" valid? And when it isn't, what kind of statistical tests can we use to compare our predictions with our observations?

These are two of many questions in the area of interpreting exercise results, the answers to which could help us to significantly enhance the credibility of our analysis of detection performance. Yet very little work is being supported in this area.

SUMMARY

- DETECTION PROCESS VERY COMPLEX
- HIGH DEGREE OF APPROXIMATION
- NO SOUND BASIS FOR ASSIGNING VALUES TO KEY PARAMETERS
- FEW ATTEMPTS TO COMPARE THEORETICAL RESULTS WITH REAL-WORLD DATA

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In summary, we have briefly reviewed the standard approach to the analysis of sonar performance. We have seen that due to the complexity of the process and the need for analytical simplicity, the level of approximation is necessarily high. Furthermore, there are several key parameters at the heart of the analysis: such as the recognition differential and the standard deviation of the signal excess distribution that, despite their importance, have not been closely scrutinized and whose values therefore must often be assumed uncritically on the basis of vague traditional "rules of thumb." Furthermore, the connection between theory and experiment, the only basis of a model's credibility, is being paid very little attention. There is clearly a lot of important work still to be done in these fields.

Now in this overview I have chosen to focus on some of the shortcomings of detection analysis rather than on its very impressive achievements. I do this, not to belittle those achievements but rather to stress the view that it is within our grasp to make detection analyses even better. In fact, the detection phase of naval warfare is perhaps the most clearly understood, scientifically modelled, and empirically supported of any of the other phases of a naval engagement. Indeed, if the purpose of analysis is to help structure, quantify and focus the debate, then the rest of the analytic community may have a lot to learn from the methods of detection analysis.

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